Flavor, Compositeness, and Dynamical Breaking of Supersymmetry

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We should be taking advantage of recent gains in our nonperturbative understanding of supersymmetric gauge theories to find the "standard" model of of dynamical supersymmetry breaking, and possibly of flavor as well. As an illustration of the possibilities for understanding the flavor hierarchy, I describe a realistic, renormalizable, supersymmetric model with a compositeness scale of $\sim 1-3$ TeV for the top quark, the left handed bottom quark, and the up-type Higgs. The top-Higgs Yukawa coupling is a dynamically generated strong interaction effect, and is naturally large, while the other Yukawa couplings are suppressed.

1. Introduction: Can SUSY Gauge Dynamics Solve Our Problems?

Holomorphy and Duality have taught us a lot of nonperturbative information about low energy dynamics of N = 1 supersymmetric gauge theories [1]. One might hope that this would turn out to be useful in understanding some long standing puzzles in particle physics.

2. The Gauge Hierarchy Problem

Dynamical Breaking of Supersymmetry (DSB) at a scale which is exponentially small when compared with the Planck scale m_P, is a potentially beautiful solution to the problem of why the weak scale is so much lower than the Planck scale [2]. Until recently only 4 examples of DSB were known [3,4], none of which yielded a realistic candidate model of particle physics [3]. We now know of several new mechanisms and many new classes of DSB models [5–13]. In the last two years we have learned that supersymmetry can break dynamically in models with classically flat directions, with non-chiral representations of the gauge group, with gauge singlet superfields, without dynamically generated superpotentials, and without any $U(1)$ R-symmetry [14].

While many of the new DSB models can be supplemented with additional sectors to yield realistic theories, no really compelling "standard model" of supersymmetry breaking has emerged. All the models require the addition of a MSSM (Minimal Supersymmetric Standard Model) sector to be realistic. Hidden sector models are not renormalizable or predictive, and do not explain the absence of flavor changing neutral currents or electric dipole moments, while visible sector gauge mediated models require that, in addition to the MSSM sector, a "messenger sector" of new, heavy, vector-like quarks and leptons be tacked on. Still, further exploration might reveal a plausible DSB model whose low energy limit contains the standard model, or at least one with room in its global symmetry group to embed the standard model gauge interactions, so that the the messenger sector could be avoided.

Note that any interpretation of the Fermilab $ee\gamma\gamma$ event involving decay into a gravitino [15–21] implies a rather low ($< \mathcal{O}(100$ TeV$)$) supersymmetry breaking scale. Since the messenger quarks and leptons should also have mass in the 30–100 TeV range [6], if this event is a signal for a light gravitino then we have an indication that the DSB and messenger sectors are the same. In fact there are several ways to merge the DSB and messenger sectors [22].

3. Flavor

Even more puzzling than the supersymmetry breaking mechanism is the explanation for the hierarchy of quark and lepton masses and mixing angles. It is intriguing to speculate that strongly

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coupled dynamics could lie behind the generational structure. For instance, in the context of supersymmetry, at least some of the superpotential couplings of the MSSM might have a dynamical origin.

A proposal along these lines was made in [23] and in [24] in which a dynamical mechanism for generating the top quark Yukawa coupling was suggested. In this "quindecuplet" scenario, a confining $SU(2)_C$ gauge theory, has as its low energy limit a 15 dimensional multiplet of composite particles, containing the top quark, left-handed bottom quark, the up-type Higgs, and the left handed tau anti-lepton. The ordinary $SU(3)_c \times SU(2)_w \times U(1)_Y$ gauge interactions can be embedded into an $SU(5)$ global symmetry of the strong interactions, under which the composite particles transform as $\mathbf{5}+\mathbf{10}$. The top quark Yukawa coupling is generated by a strong coupling effect of confinement [25] and the bottom quark mass is generated through an higher-dimension operator arising from Planck scale physics. Viable three-generation models, employing all or part of this mechanism with the compositeness scale near to the Planck scale, were proposed in [24]. However, the compositeness scale must be very high or proton decay would be too rapid. Hence, other than the postdiction of qualitative features of the fermion mass hierarchy, these models make no predictions.

Here I would like to describe a version of the quindecuplet theory in which the proton is stable, and the compositeness scale of the top quark can be low, ~ 1 TeV. The model is realistic and is a good laboratory to study possible low energy signals which could arise from compositeness [26]. The main difference with the model of [24] is that all components of the τ lepton are fundamental particles—there is a composite particle with the gauge quantum numbers of the left handed tau anti lepton but it must carry baryon number $+1$ and so is identified as a new, exotic "triquark" particle, the $\bar{E}$. One family of quarks and leptons results from the particle content shown in table 1. The $\mathbf{N}, \mathbf{N}', \bar{\mathbf{N}}, \bar{\mathbf{N}}'$ particles are given large masses—and integrating them out will result in the nonrenormalible operators responsible for the bottom quark mass. The fifteen light composite fields of this model are

Table 1
One Family Composite Model

Preon Field	$SU(2)_C$	$SU(3)_c$	$SU(2)_w$	$U(1)_y$
$\mathbf{d}$	2	3	1	$-1/3$
$\mathbf{h}$	2	1	2	$1/2$
$\mathbf{n}, \mathbf{N}, \mathbf{N}', \bar{\mathbf{N}}, \bar{\mathbf{N}}'$	2	1	1	0
$\bar{d}, \bar{D}$	1	3	1	$1/3$
$\bar{H}$, ℓ	1	1	2	$-1/2$
E	1	1	1	-1
$\bar{e}$	1	1	1	1

$$q \sim \begin{pmatrix} t \\ b \end{pmatrix} \sim \mathbf{dh} \qquad \bar{t} \sim \mathbf{dd} \qquad H \sim \mathbf{hn} \qquad D \sim \mathbf{dn} \qquad \bar{E} \sim \mathbf{hh} \ , \tag{1}$$

which we identify with the top and left handed bottom quarks, the up-type Higgs, and an exotic "diquark" and "triquark". To get three families the model is triplicated—three different $SU(2)_C$'s with different compositeness scales are introduced. The quark mass hierarchy is a result of the 3 different compositeness scales.

Here I will briefly summarize how the model reproduces the particle masses and mixing angles.

3.1. Higgs, D and E masses

The tree level superpotential contains the terms

$$W_{\text{tree}} \supset \eta^H \mathbf{hn}\bar{H} + \eta^D \mathbf{dn}\bar{D} + \eta^E \mathbf{hh}E \ . \tag{2}$$

The first term gives the infamous "μ" Higgs mass term of the MSSM, of size η^H times the compositeness scale. Hence unless we assume η^H is extremely small the compositeness scale Λ should not be too far above the weak scale. Similarly, the second two terms result in D and E masses proportional to $\eta^D\Lambda$ and $\eta^E\Lambda$.

3.2. The Top Mass

Below the confinement scale, a superpotential is generated dynamically for the composite particles [25]

$$W_{\text{dynamical}} \propto q\bar{t}H + qqD + \bar{t}D\bar{E} \ . \tag{3}$$

The first term, the top-Higgs Yukawa coupling, is a nonperturbative effect which we expect to be

large—implying that $\tan\beta$ could be small. Note that the D must be assigned baryon number $-2/3$ and the E carries baryon number of 1.

3.3. The Bottom Mass

This mass must come from the term

$$W_{\text{effective}} \supset \frac{1}{M}\mathbf{dh}\bar{b}\bar{H} \ , \tag{4}$$

which results in a b-quark Yukawa coupling of order Λ/M, where Λ is the compositeness scale. This nonrenormalizable term results from integrating out the $\mathbf{N}, \bar{\mathbf{N}}$ preons if the tree level superpotential includes the terms

$$W_{\text{tree}} \supset M_N \bar{\mathbf{N}}\mathbf{N} + \kappa^d \mathbf{d}\bar{\mathbf{N}}\bar{d} + \lambda^H \mathbf{hN}\bar{H} \ . \tag{5}$$

3.4. The Light Quark Masses

In order to give the charm and up quarks mass, it is necessary that the model be triplicated–that is two more confining $SU(2)$ groups, which get strong at scales Λ_1 and Λ_2 respectively, produce two more sets of 15 light composite particles. These include the first and second quark doublets, the $\bar{u}$ and the $\bar{c}$, with dynamical couplings to two additional composite up-type Higgses. The latter, as well as the additional D and E particles, will combine with elementary particles to get large masses of order $\Lambda_{1,2}$, however off-diagonal superpotential couplings to the down-type Higgses will cause the heavy up-type Higgses to mix with the lightest H by amounts of order Λ_3/Λ_2, Λ_3/Λ_1. The light up-type Higgs is actually a mixture of the three composite Higgses–which explains the charm and up masses as dynamical effects. The compositeness scale for the second family quarks is > 200 TeV—those of you who are refugees from extended technicolor model building will recognize this scale as being high enough to keep the model safe from overly large $K - \bar{K}$ mixing.

The down and strange quark masses arise in a manner similar to the bottom quark mass. The number of doublets for each of the $SU(2)$'s is chosen such that if all the $SU(2)$ couplings are equal at short distance and the differance in confinement scales is due entirely to different masses $M_{1,2,3}$ for the three sets of heavy preons, we obtain the natural order of magnitude relations for quark masses and mixing angles

$$\begin{array}{c} m_d/m_s \sim \sqrt{m_u/m_c} \sim \theta_{12} \sim (M_2/M_1)^{(1/3)} \\ m_s/m_b \sim \sqrt{m_c/m_t} \sim \theta_{23} \sim (M_3/M_2)^{(1/3)} \\ \theta_{13} \sim (M_3/M_1)^{1/3} \ . \end{array} \tag{6}$$

The M_i's can be chosen such that these all work to within a factor of 2 or 3.

3.5. Lepton Masses

Since the leptons and the down-type Higgs are both fundamental particles, renormalizable lepton-Higgs couplings are allowed. The lepton mass hierarchy could be put in by hand. However work is in progress on an attempt to explain the lepton Yukawa coupling hierarchy via large anomalous dimensions, induced by a superpotential coupling of the lepton doublets to the strongly coupled preons $\mathbf{h}, \mathbf{N}', \bar{\mathbf{N}}'$ [22]. (This can be done in a way consistent with baryon and lepton number symmetries.)

3.6. Supersymmetry and Electroweak Symmetry Breaking

A low scale for the messenger sector is preferred in this model. If the supersymmetry breaking is communicated above the compositeness scale of the second family, (as in hidden sector models with supergravity as the messenger,) then strong renormalization effects will ensure that the first two generation squark masses are not degenerate. Furthermore the squark masses will align with the up-type rather than the down-type quark masses. Thus unless the first two families of squarks are rather heavy, hidden sector supersymmetry breaking will necessarily lead to overly large $K - \bar{K}$ mixing.

A supersymmetry breaking sector such as one of the gauge mediated DSB models of ref. [6,15] can easily be appended to this model, resulting in a realistic picture with no large flavor changing neutral currents.

As usual the Higgs potential and electroweak symmetry breaking is determined by the supersymmetry breaking sector. However, unlike in the usual gauge mediated scenario, the up-type Higgs is a composite, and its supersymmetry breaking mass is not easily predicted. It is concievable that $\tan\beta$ could be less than 1, even in a gauge medi-

ated scenario.

3.7. Experimental Tests

With a sufficiently low third family and Higgs compositeness scale, [26,22] detectable deviations from the standard model could be found in the ρ parameter, $B-\bar{B}$ mixing and CP violation, the $Z \to b\bar{b}$ rate, and the rate and the lepton distributions and polarization for $b \to s\ell^+\ell^-$. A remarkable feature of the quindecuplet model is an approximate $SU(6)$ global symmetry which allows all of these effects to be predicted in terms of $\tan\beta$ and a single strong interaction coefficient [26]. Future precision measurements of Higgs and top couplings would also show small deviations from the standard model.

4. Conclusions

There still remains much exploration to do of strongly coupled supersymmetric gauge theories. Both dynamical supersymmetry breaking and the fermion mass hierarchy could potentially be explained with new strong interactions. It is encouraging that construction of realistic supersymmetric composite models is possible. Although I have no example, it is especially tempting to speculate that the same new strong interactions could account for both the gauge and flavor hierarchies—that dynamical supersymmetry breaking will occur in some (yet to be discovered) composite model of quarks and leptons which also sheds light on the flavor puzzle.

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